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# **Cost Effectiveness of Crystalline Silico-Titanate and Resorcinol-Formaldehyde Ion Exchange Resins, and Enhanced Sludge Washing with and without Chromium Oxidation**



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*Submitted to:* **General Distribution**

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## Nomenclature

CrOx	= Chromium oxidation
CS100	= Duolite™ CS-100 ion exchange resin
CST	= Crystalline silico-titanate
DOE	= Department of Energy
ESW	= Enhanced sludge washing
HLW	= High-level waste
IX	= Ion exchange
LLW	= Low-level waste
RF	= Resorcinol formaldehyde
TWRS	= Tank Waste Remediation System
UST	= Underground Storage Tank

## Caveats

This analysis has been funded by the Department of Energy, Office of Science and Technology (EM-50); however, the conclusions presented here are not necessarily all endorsed by the DOE. Due to its limited scope, this study is based on a Top-Down rather than Bottoms-Up analysis. In other words, rather than develop a Bottoms-Up process model for Hanford UST remediation for this study, a Top-Down approximation of the TWRS Aspen-based Bottoms-Up model was developed. It is not the author's intent to present this study as the only method for calculating a cost benefit for these technologies. Undoubtedly, there are numerous improvements which can be made to this analysis, and may be made with time. This study was performed with the intent to give decision makers an estimate of the potential cost benefit for these technologies within a factor of two to three uncertainty.

Additionally, it has been the author's experience during the past several years that performance and cost data, whether related to solids-based or liquid-based waste processing, has been in general a subject of much debate by the technical community. Consequently, it is not the author's intent to claim the data used in this study to be globally accepted at this point in time, or even relevant one year from now. The uncertainty associated with UST waste characterization makes it necessary to often revise a study such as this. Therefore, the results of this study should be viewed in context of the referenced resources being the most relevant available as of May 1997.

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## Conclusions

This report summarizes the results of an updated study intended to determine the affect on remediation cost of a broad range of processing alternates for underground storage tank (UST) waste at Hanford. In particular, the analyses were updated to account for new waste inventories, and differentiate between Phase I and Phase II of the Privatization effort. Separation of Phase I from Phase II provides some insight into cost savings which may occur specifically during the next ten to fifteen years. The broad range of processing alternatives included in this study are (1) no treatment of solids-based waste, (2) enhanced sludge washing (ESW) of solids-based waste, (3) ESW plus chromium oxidation (ESW+CrOx) of solids-based waste, (4) CS100 ion exchange (IX) processing of liquid-based waste, (5) crystalline silico-titanate (CST) IX processing of liquid-based waste, and (6) resorcinol-formaldehyde (RF) IX processing of liquid-based waste. It is not the intent of this study to claim a baseline set of technologies for remediating the UST waste at Hanford; but rather, provide a cost matrix incorporating the synergistic effects of solids-based and liquid-based processing for a number of potential treatment options. This permits the Decision Maker to select their own baseline for comparison against alternate technologies.

Figures 1 and 2 show potential cost savings for the combined solids-based and liquid-based waste processing by way of the relevant technologies.

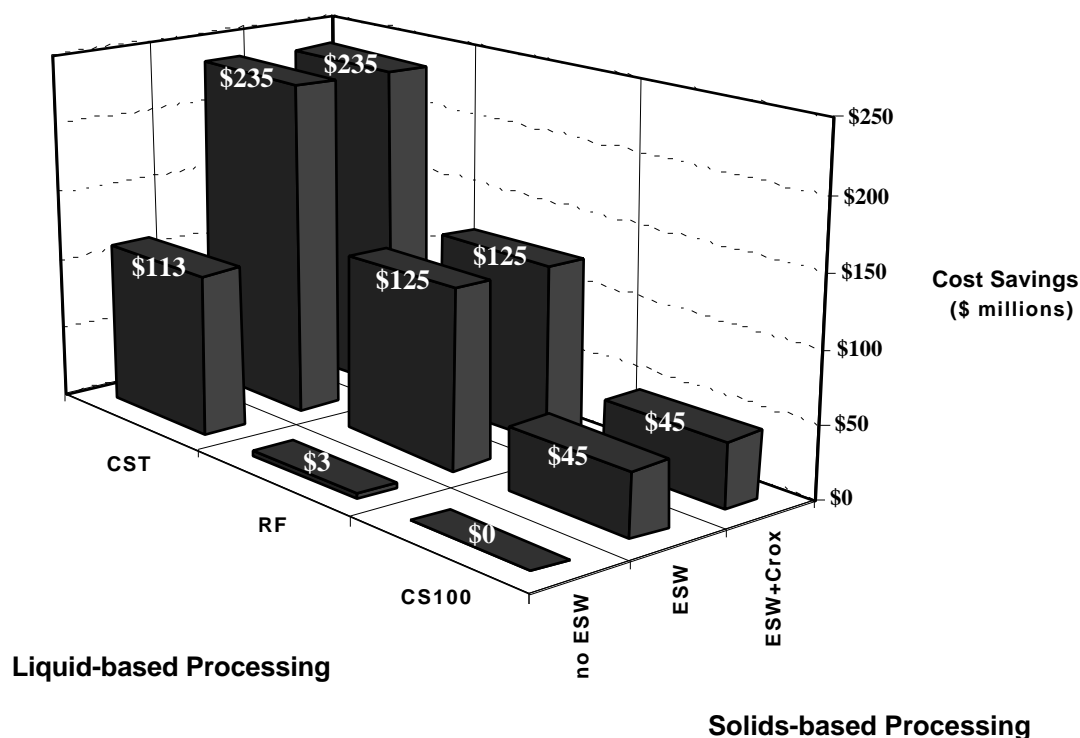
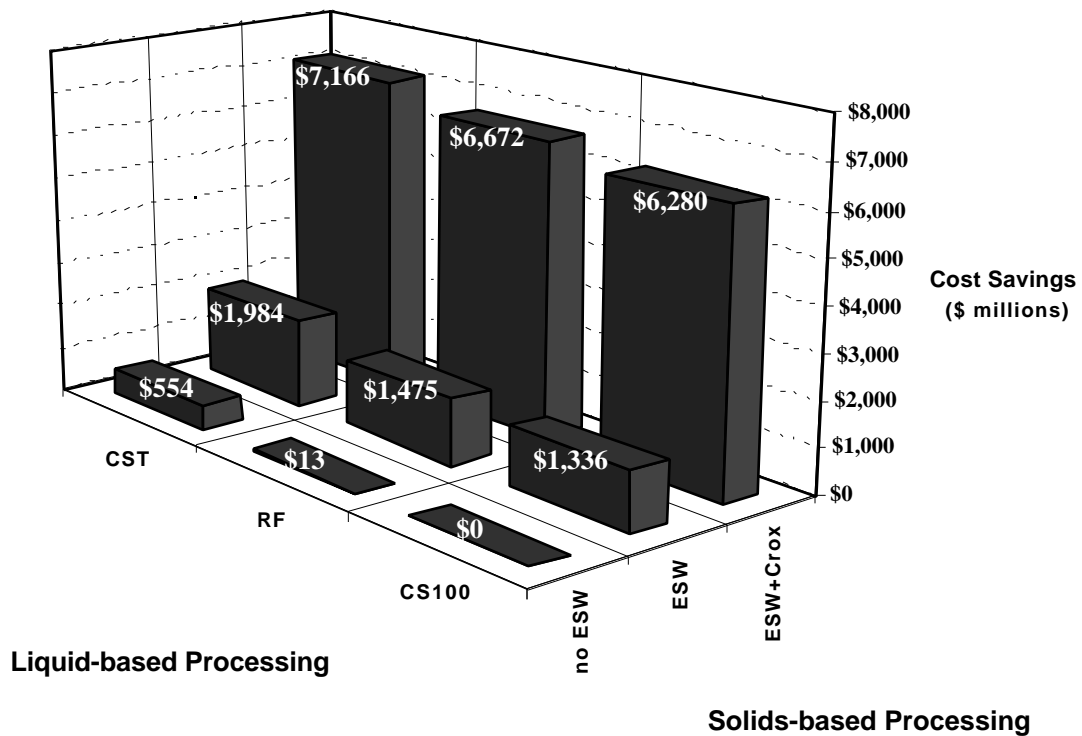


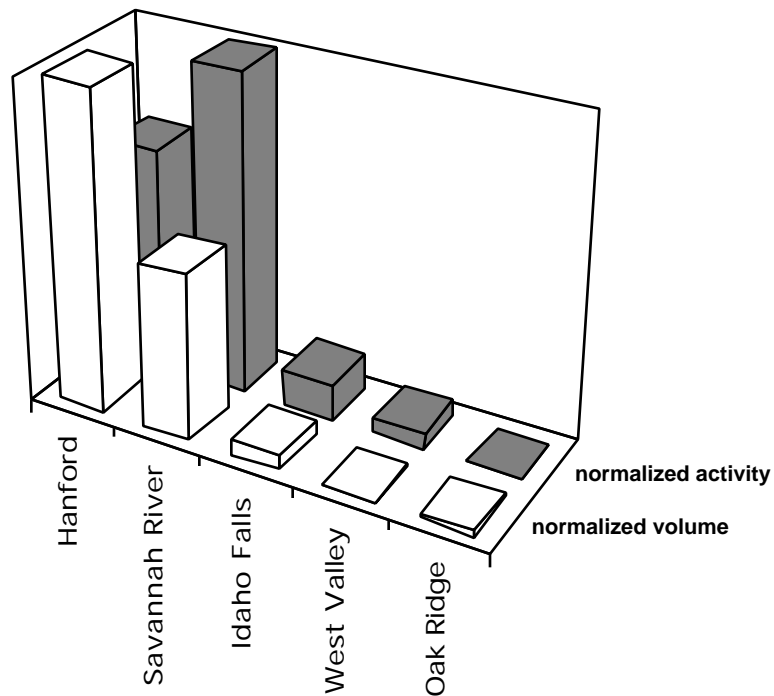
Figure 1. Sludge washing and IX cost savings for Phase I of Privatization.



**Figure 2. Sludge washing and IX cost savings for Phase II of Privatization.**

## 1. Introduction

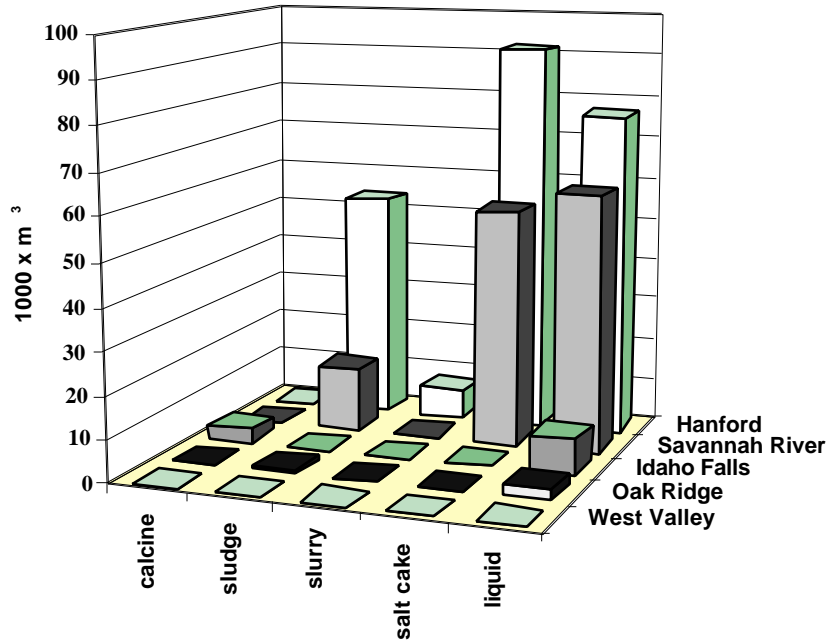
There exists approximately 100 million gallons (~400,000 m<sup>3</sup>) of radioactive waste in underground storage tanks (USTs) at five DOE sites across the United States [1&2]. Sixty-five million gallons are stored at Hanford and the other 35 million gallons are at the Savannah River, Idaho Falls, West Valley, and Oak Ridge sites. Figure 3 shows these DOE sites and their relative waste volumes and activities (i.e., curies). The U. S. Department of Energy (DOE) is responsible for permanently immobilizing this tank waste which consists of high-level waste (HLW) and low-level waste (LLW). The current plan for HLW disposal is immobilization as glass and permanent storage in an underground repository; whereas, LLW can generally be disposed of subsurface at the point of origin. Currently, the vast majority of underground storage tank waste at the five DOE sites can not be classified as LLW, and consequently can not be disposed of subsurface. Since subsurface disposal as LLW is significantly less expensive than disposal in an underground repository as HLW, it is advantageous to separate most of the radionuclides from the 100 million gallons of waste. The separated concentrated radionuclides would then be disposed of as a smaller volume of HLW.



**Figure 3. Underground storage tank waste volume and activity at the DOE sites [1].**

Of the 100 million gallons of waste stored in underground tanks, approximately 80 vol% will be retrieved in a liquid-based form and is amenable to HLW volume reduction by radionuclide concentration. Liquid-based processing can be applied to the supernate, salt cake, liquid portion of the slurry waste, sludge interstitial liquid, and calcine. Calcine can be processed as liquid following dissolution with acid. Cesium-137 contributes about 95% of the activity in the liquid-based waste, with the remaining activity primarily due to strontium-90. The other 20 vol% of UST waste consists of sludge and slurry solids. The sludge-solids and slurry solids will be defined in this study as solids-based waste. The sludge-solids and slurry solids consist of well over 99 wt% nonradionuclides. Without solids-based processing, the non-radionuclides will dictate a very large volume of immobilized HLW for the underground repository. Therefore, separation of the nonradionuclides from the sludge-solids (such as aluminum, chromium, sodium, and phosphorus) is an essential step in reducing the final HLW glass volume sent to the repository. The aluminum,

chromium, sodium, and phosphorus separated from solids-based waste can be disposed of as LLW. Figure 4 shows the amount of each waste form at each of the five DOE sites.

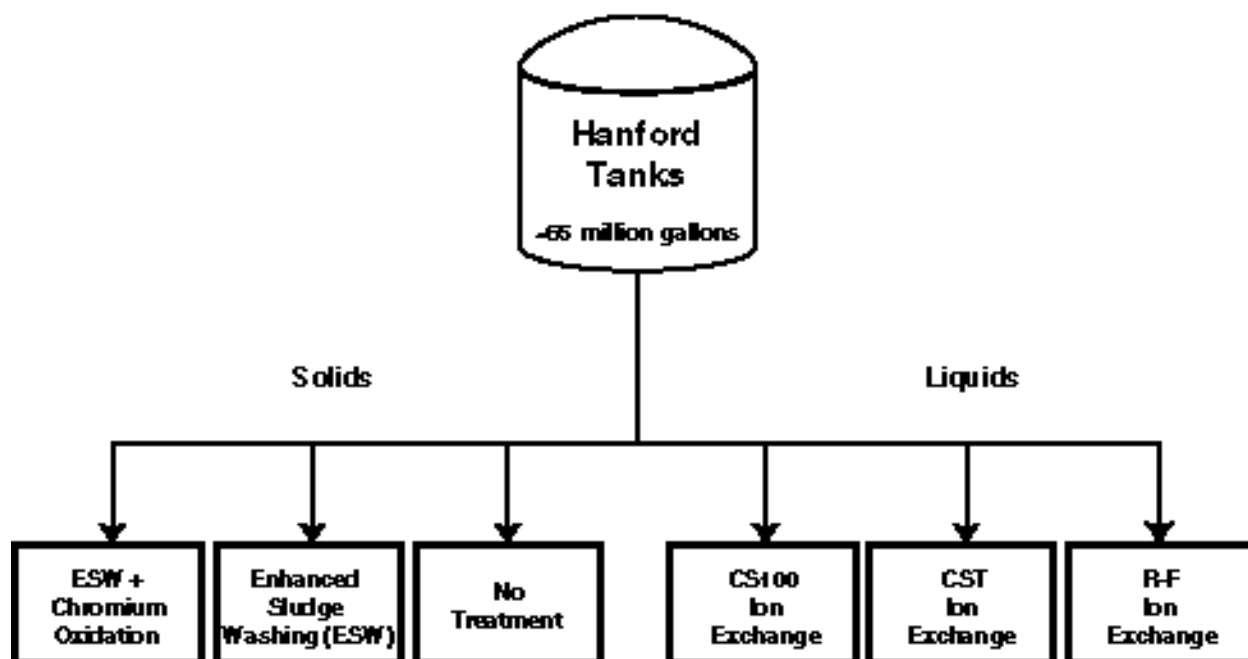


**Figure 4. Waste form in underground storage tanks at each DOE site [1].**

## 2. Applicability

In this study four advanced technologies have been selected for potential use at the Hanford site. These technologies are (1) crystalline silico-titanate (CST) and (2) resorcinol formaldehyde (RF) ion exchange (IX) resins for separation of cesium from liquid-based waste, and (3) enhanced sludge washing (ESW) with and without (4) chromium oxidation for separation of Al, Cr, Na and P from solids-based waste. These advanced technologies will be compared with the baseline scenarios of no treatment of solids-based waste and CS100 IX processing of liquid-based waste. While these technologies may be applicable in some cases at the other DOE sites, this study is limited to only Hanford at this time. Figure 5 shows the baseline and innovative technologies that have been considered for this study.





**Figure 5. Baseline and innovative technologies for Hanford tank waste.**

Approximately 50 million gallons ( $\sim 187,000 \text{ m}^3$ ) of the UST waste stored in underground tanks at Hanford is amenable to cesium separation by CS100, CST, and RF IX resins (Figure 5). Approximately 15 million gallons ( $\sim 56,000 \text{ m}^3$ ) of the UST waste stored in underground tanks at Hanford is amenable to Al, Cr, Na and P separation by ESW with and without chromium oxidation (Figure 5). Figure 6 displays the volume of liquid-based and solids-based waste at the respective DOE sites.

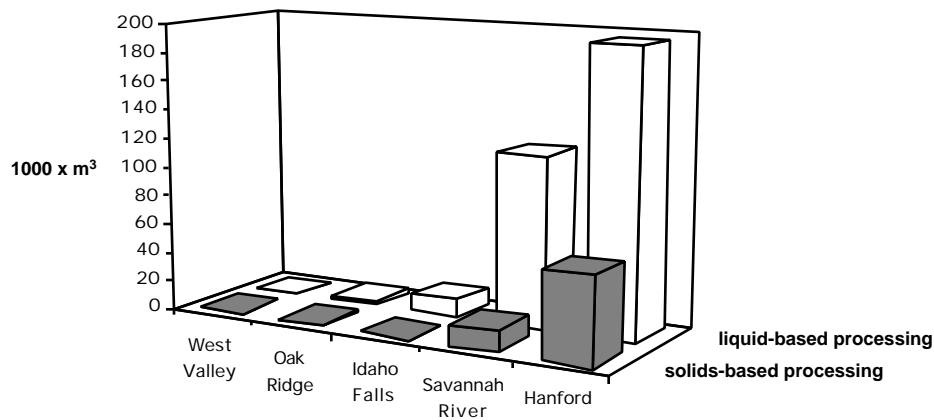
The reasons for which this study does not include the sites other than Hanford are as follows:

Savannah River - The current sodium tetraphenyl borate precipitation process planned for cesium separation at the Savannah River Site (SRS) is based on in-tank processing; whereas, the advanced CST and RF resins of this study are being developed for out-of-tank IX column processing. While modified a form of CST could easily be applied to in-tank batch processing, or column-based IX could be retrofitted at SRS, the extent of the system differences for these two types of processes are too significant for the scope of this study. A process similar to ESW, referred to as Extended Sludge Processing (ESP), has been developed and is being used at Savannah River. Since ESP is currently in use, it can be considered the baseline at this time.

West Valley - The waste at West Valley, a site in New York that contains two USTs, has already undergone most of its planned remediation by way of cesium separation by zeolite ion exchange, and sludge washing.

Idaho Falls - While the waste at Hanford, Savannah River, and Oak Ridge is alkaline; the waste at Idaho Falls is primarily calcine and a small amount of acid which eventually will be calcined as well. Should the calcine be processed for cesium separation, it will likely first be converted to an acidic liquid waste; however, since the calcine bins were designed for a 500 year life, the calcine form can be considered temporarily immobilized. Therefore, studies related Idaho Falls waste remediation are not as pressing as those related to the other sites.

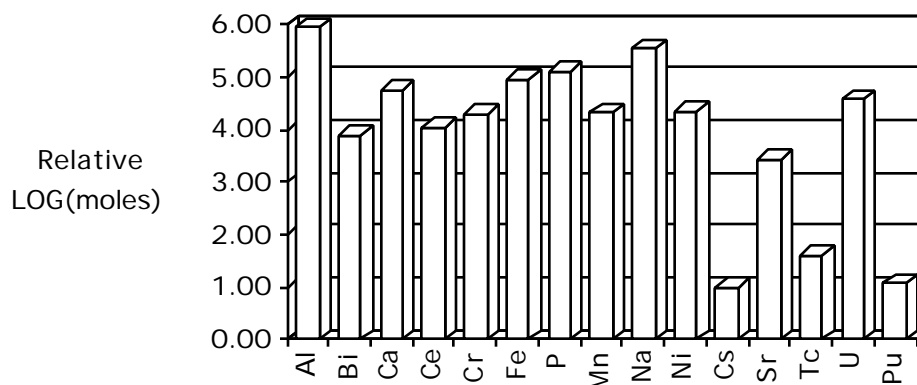
Oak Ridge - While the waste at Oak Ridge has already been used for a significant demonstration of IX technology due to their flexible operations, it has not been included in this cost study due the limited volume of waste as compared to Hanford (2 vol% that of Hanford). The most significant cost savings for innovative technologies will occur at Hanford and Savannah River, due to their large waste volumes.



**Figure 6. Waste processing form at each DOE site [1].**

Figure 7 shows the relative chemical composition of the solids-based waste at Hanford. Due to the high non radionuclide waste content of the sludge-solids and the greater difficulty processing solids-based compared to liquid-based waste, the solids-based waste has a much greater effect on the final volume of HLW glass sent to the underground repository than that resulting from liquid-based waste (TWRS Flowsheet). In particular, the aluminum, chromium, sodium, and phosphorus in the sludge-solids have a large impact on the final volume of HLW

glass. This is due to their high concentration in the sludge, and/or their significant affect on the HLW glass forming and glass chemical stability. Even with the ESW plus chromium oxidation, radionuclide loading in the HLW glass due to the solids-based waste is about fifty-times less than that permitted by radionuclide heat generation alone [3]. Consequently, chemical processing which significantly reduces the sludge nonradionuclide concentration can have a very large impact on the overall remediation cost.



**Figure 7. Hanford prewashed solids composition.**

### 3. Technology Descriptions

This study is updating an original set of cost studies (5, 6, &7) utilizing the Tank Waste Remediation System (TWRS) Flowsheet for defining the Hanford waste characteristics, and CS100 IX resin for processing liquid-based waste.(4) Some of the significant performance characteristics of the TWRS Flowsheet are as follows.

- IX column LLW effluent (not the final LLW form, see Figure 8) meets Class A waste requirements for cesium, see Section 2.5.3 of Reference 4.
- The cesium concentration on the resin is in equilibrium with the cesium concentration in the IX feed prior to regeneration. This yields maximum radionuclide loading on the resin by the use of multiple IX columns in series.
- The CS100 organic resin survives ten regeneration cycles prior to disposal [4], and the Resorcinol-Formaldehyde organic resin survives four regeneration cycles prior to disposal. [8]
- The organic resins can be disposed of as LLW or HLW following the final elution, without a significant impact on the overall remediation cost. Since the resins are essentially volatilized, the corresponding contribution to the overall HLW volume is insignificant. The only potential affect on the remediation cost due to organic resin

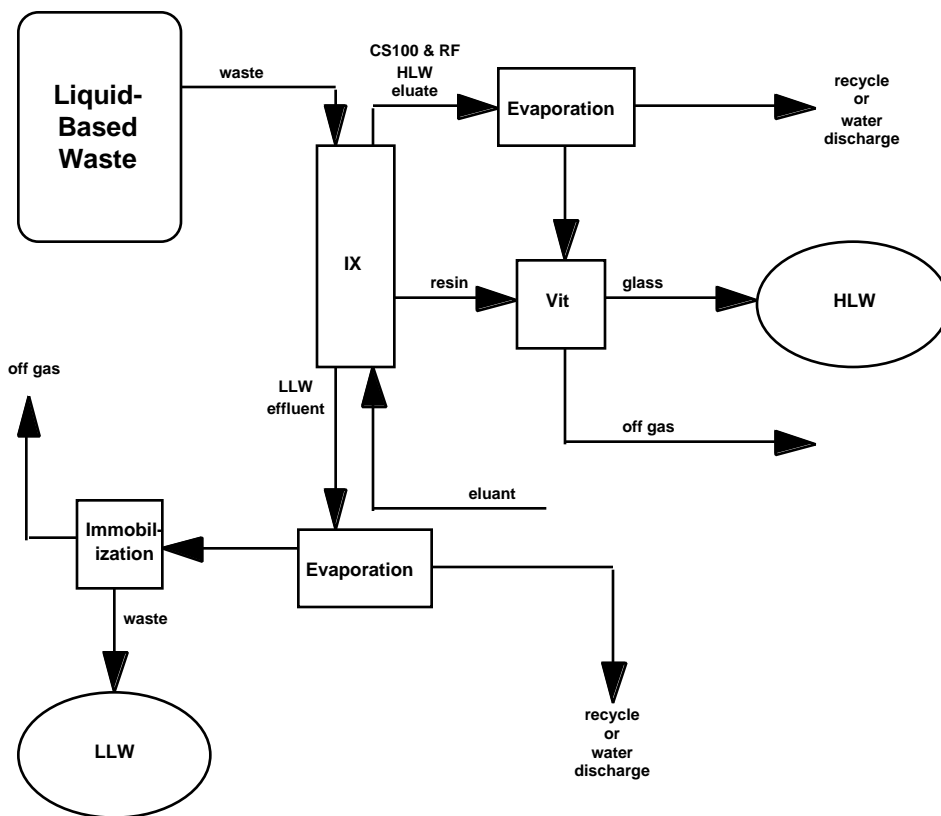
disposal is the impact on the off-gas system, which was shown to be insignificant if disposed as LLW or HLW (see Reference 5 where it is shown that the resin contribution is ~1 wt% of the overall off-gas throughput). This assumes the resin destruction does not significantly complicate the HLW vitrification process.

- The quantity of HLW glass produced is based upon waste blending.

The results of the original cost studies were distributed to the appropriate technical community for review, and their comments with the author's response are recorded in Reference [9]. Much of this updated study is based upon the TWRS Privatization Process Technical Description [10]. For this update, the tank waste inventories and glass specifications were based upon Phase I and Phase II of the Privatization effort.

### **3.1 CS100, CST, and RF**

Duolite<sup>TM</sup> CS100 IX resin was assumed the remediation cost baseline for cesium separation from liquid-based waste for this study, in contrast to RF and CST resins assumed to be the alternate technologies. This is due to the fact that CS100 has been offered commercially in the past; whereas, RF and CST resins have not yet been completely commercialized. CS100, RF (6), and CST (5) resins are all used in a conventional out-of-tank IX column. The CS100 and RF resins are organic, regenerable, and are to be disposed of as LLW or HLW following the final elution. The CST resin is inorganic, nonregenerable, and will be disposed of as HLW. The generalized cesium separation processes are shown in Figure 8.



**Figure 8. CS100 and CST ion exchange processes for Hanford liquid-based wastes.**

### 3.2 ESW/Chromium Oxidation

Dilute caustic washing alone was assumed the remediation cost baseline for Al, Cr, Na, and P separation from solids-based waste for this study, in contrast to ESW, and ESW plus chromium oxidation assumed to be the alternate technologies. This is due to the fact that dilute caustic washing requires no further development; whereas, ESW and ESW plus chromium oxidation may require further efforts to at least define their capabilities. Dilute caustic washing essentially removes only the sludge interstitial liquid, see Section 5.5.1 of the TWRS Flowsheet[4]. ESW involves some dissolution of the sludge with moderately caustic solution, in addition to the removal of interstitial liquid. ESW with chromium oxidation includes an extra step which increases the dissolution of chromium. The degree of chromium dissolution has been a subject of much debate for which the author does not attempt to settle here, the basis used in this study is clearly referenced and will undoubtedly become out-dated more quickly than preferred. The ESW as defined by the TWRS Flowsheet and shown in Figure 9, is achieved in-tank and involves mixing, settling, and decant processes.



**Figure 9. The Enhanced Sludge Wash process.**

#### **4. Analysis**

When using an elutable organic IX resin (CS100 & RF), it is essentially the amount of (1) sodium in the waste being treated, plus the (2) sodium added to neutralize the cesium loaded eluate, that dictates the liquid-based waste contribution to the final amount of HLW glass. The cesium versus sodium resin specificity dictates the amount of sodium which is loaded from the waste onto the resin simultaneously with the cesium. The cesium loading capacity of the resin dictates the total number of resin regenerations, which affects the total amount of nitric acid required for elution, which dictates the amount of NaOH required for neutralization of the eluate for interim tank storage prior to HLW immobilization.

In contrast, it is essentially the resin mass which dictates the amount of HLW glass when using a nonelutable inorganic IX resin, such as CST, for cesium separation. The inorganic resin is essentially the same as the non radionuclide waste, and must be treated similarly during the HLW immobilization. Consequently, due to the fact that less than 10 wt% of the loaded inorganic resin is due to the sodium and cesium in the waste, the majority of the contribution to the final HLW glass from inorganic IX is due to the original resin material [5].

Therefore, cost effectiveness for the organic and inorganic resins is based on the following characteristics. The CS100 and RF resins, (1) resin specificity for cesium versus sodium, and (2) resin capacity for cesium, dictate the organic resin cost effectiveness. For the CST resin, it is the (1) resin capacity for cesium, and (2) lack of regeneration equipment, which dictate the resin cost effectiveness.

##### **4.1 Waste Characteristics**

Hanford waste characteristics for this updated cost study are based upon Stream #5-Figure 14 of Reference 10 for Phase I, and Stream #6 - Figure 14 of Reference 10 for Phase II.

## 4.2 CS100, CST, and RF Performance

A complete “bottoms-up” resin performance model for comparison between differing IX resins requires knowledge of (1) cesium and sodium loading, (2) cesium and sodium elution, and (3) interim storage neutralization. Generally speaking, it is only the cesium loading which has been well-characterized by the developers. For instance, resin distribution coefficients (better known as the  $k_d$  factor) would need to be determined for both cesium and sodium to estimate specificity, for both loading and elution conditions. Additionally, these  $k_d$ s need to be determined for the waste conditions a study is based upon. While some of these data have been determined for some waste conditions, finding a complete set of data for all waste conditions of this study, for each resin of interest, was not possible within the scope of this study. Therefore, a top-down rather than bottoms-up model was developed for comparing resins. This approach was used by the author in his previous cost study [6].

In general terms, the top-down model groups the loading, elution, and neutralization into a single step for the organic resins. Since elution and neutralization are not required for an inorganic resin, the inorganic resin model used for this study is more of a bottoms-up focused on resin loading alone. As determined previously for TWRS blended waste defined in Reference 4, the ratio of cesium to sodium in the tank waste, to that in the cesium separated by organic IX, is shown by Equations 1 and 2 from Reference 6 (Table 3).

$$\frac{(m_{Cs} / m_{Na})_{ne}}{(m_{Cs} / m_{Na})_f} = 146 \quad \text{for the CS100 resin} \quad \text{Equation 1}$$

where  $m$  = moles  
 $ne$  = neutralized eluate  
 $f$  = waste feed to IX

$$\frac{(m_{Cs} / m_{Na})_{ne}}{(m_{Cs} / m_{Na})_f} = 593 \quad \text{for the RF resin} \quad \text{Equation 2}$$

Equations 1 and 2 incorporate the effects of (1) cesium with simultaneous sodium loading on the resin, (2) cesium with simultaneous sodium elution from the resin, and (3) NaOH neutralization for interim storage of the cesium loaded nitric acid used to elute the resin. Equations 1 and 2 reflect the results of an ASPEN systems model (bottoms-up) incorporating detailed IX performance and interim storage neutralization from which the TWRS Flowsheet was developed

(Reference 4). The utility of Equations 1 and 2 lies in the prediction of the amount of sodium which must be disposed of in the final HLW glass along with the cesium. As mentioned earlier, for organic IX resin it is the sodium which dictates the liquid-based waste contribution to the final volume of HLW glass.

Phase 1 (based on soluble components of tank waste, Stream #5 - Figure 14 of Reference 10):

$$(m_{Cs}/m_{Na})_f = [(610 \text{ kg-Cs})(1 \text{ gmole}/0.137 \text{ kg-Cs})]/[(10,600,000 \text{ kg-Na})(1 \text{ gmole}/0.023 \text{ kg-Na})]$$

$$= 9.661 \times 10^{-6}$$

It is assumed essentially all the cesium is separated from the waste. Using IX columns in series allows saturation of the resin at equilibrium conditions with the cesium IX feed concentration. This assumption is not unrealistic for actual operations, and yields maximum cesium loading of the resin.

$$\frac{\left[ \left( 610 \text{ kg-Cs} / m_{Na} \right) (1 \text{ gmole-Cs} / 0.137 \text{ kg-Cs}) \right]_{ne}}{\left( 9.661 \times 10^{-6} \right)_f} = 146$$

$$m_{Na}(\text{CS100}) = 3,157,000 \text{ gmole-Na (72,600 kg-Na)}$$

Similarly;

$$m_{Na}(\text{RF}) = 777,300 \text{ gmole-Na (17,870 kg-Na)}$$

Phase 2 (based on proposed IX feed, Stream #14 - Figure 14 of Reference 10):

$$(m_{Cs}/m_{Na})_f = [(1840 \text{ kg-Cs})(1 \text{ gmole}/0.137 \text{ kg-Cs})]/[(65,100,000 \text{ kg-Na})(1 \text{ gmole}/0.023 \text{ kg-Na})]$$

$$= 4.745 \times 10^{-6}$$

If it is assumed essentially all the cesium is separated from the waste;

$$\frac{\left[ \left( 1840 \text{ kg-Cs} / m_{Na} \right) (1 \text{ gmole-Cs} / 0.137 \text{ kg-Cs}) \right]_{ne}}{\left( 4.745 \times 10^{-6} \right)_f} = 146$$

$$m_{Na}(\text{CS100}) = 1.939 \times 10^7 \text{ gmole-Na (445,900 kg-Na)}$$

Similarly;

$$m_{Na}(\text{RF}) = 4.773 \times 10^6 \text{ gmole-Na (109,800 kg-Na)}$$



The CST resin performance for Phase I and Phase II is based upon a wide range of testing directed by Sandia National Laboratory [11]. The total CST resin required to process the liquid waste is based upon a  $k_d$  of 1800 for Phase I and 1700 for Phase II. These  $k_d$ s were determined for the specific blended waste of Phase I and Phase II as shown in Table 1. As shown in Table 1, the  $k_d$ s determined from testing [11] required some adjustment for the IX feed conditions of Phase I and Phase II. It was decided the test results from DSSF-7 simulant should form the basis for estimating the  $k_d$ s for Phase I and II. Reference 11 indicated the cesium to sodium concentration ratio, and as well as the potassium concentration, significantly affected the  $k_d$  as would be expected since  $\text{Na}^+$  and  $\text{K}^+$  both compete with  $\text{Cs}^+$  exchange on the IX resin. The adjustment factors shown in Table 1 were estimated from figures in Reference 11. It can be seen in Table 1, that the only indication of a significant difference between the DSSF-7 simulant used to ascertain the  $k_d$  in the laboratory [11], and Phase I and II waste is the potassium concentration. Consequently, the  $k_d$  was adjusted for potassium concentration in accordance with Figure 5 of Reference 11. The final  $k_d$ s were determined by multiplying the baseline value by the adjustment factors.

<b>Table 1. Waste characteristics affecting CST resin performance.</b>				
	<b>DSSF-3.75 [11]</b>	<b>DSSF-7 [11]</b>	<b>Phase I<sup>a</sup></b>	<b>Phase II</b>
$\text{Na}^+ (\text{M})$	3.75	7.0	7.0	7.0
$\text{K}^+ (\text{M})$	0.51	0.95	0.01	0.03
$m_{\text{Cs}}/m_{\text{Na}} (\times 10^5)$	7.7	7.7	12	0.5
$\text{K}^+$ adjustment <sup>b</sup>		baseline	3.3	3.1
$m_{\text{Cs}}/m_{\text{Na}}$ adjustment <sup>c</sup>		baseline	1	1
$k_d$	1250 <sup>d</sup>	550 <sup>d</sup>	1800 <sup>e</sup>	1700 <sup>e</sup>
<sup>a</sup> Phase I tank waste conditions were assumed concentrated to 7 <u>M</u> Na prior to IX for maximum $\text{Cs}^+$ loading. <sup>b</sup> Determined from Figure 5 of Reference 11. <sup>c</sup> Determined from Figure 4 of Reference 11. <sup>d</sup> Test based <sup>e</sup> Estimated with adjustment factors.				

$$\text{Phase I} \quad (3.3)(1)(550) = 1800$$

$$\text{Phase II} \quad (3.1)(1)(55) = 1700$$

As done with the organic resins, the total amount of CST resin required for Phase I and II can be estimated assuming separation of essentially all the cesium by use of IX columns in series.

Phase I:

$$k_d \text{ (CST)} = \frac{(610,000 \text{ g} - \text{Cs} / \text{X g} - \text{resin})}{(610,000 \text{ g} - \text{Cs} / 6.58 \times 10^{10} \text{ ml} - \text{waste})} = 1800$$

Where the waste volume is determined from Stream #5 - Figure 14 of Reference 10, and adjusted for concentration of sodium from 6.3 M to 7.0 M prior to IX. This provides for maximum cesium loading on the resin without precipitating sodium.

$$\text{waste volume} = 7.34 \times 10^{10} \text{ ml} \frac{(6.3 \text{ M} - \text{Na})}{(7.0 \text{ M} - \text{Na})} = 6.58 \times 10^{10} \text{ ml}$$

Upon rearranging  
 $\text{X g-resin} = 36.6 \times 10^6 \text{ g-resin (36.6 MT-resin)}$

Phase II:

$$k_d \text{ (CST)} = \frac{(1,840,000 \text{ g} - \text{Cs} / \text{X g} - \text{resin})}{(1,840,000 \text{ g} - \text{Cs} / 4.05 \times 10^{11} \text{ ml} - \text{waste})} = 1700$$

Upon rearranging  
 $\text{X g-resin} = 238.2 \times 10^6 \text{ g-resin (238.2 MT-resin)}$

#### 4.3 ESW Performance

The effectiveness of Enhanced Sludge Washing (ESW) has been revised from the TWRS Flowsheet [4] for the Privatization effort [10]. Table 2 shows the revised ESW separation factors for the Privatization effort. As can be seen in Table 2, if chromium oxidation is used with ESW, the separation of chromium from the sludge increases from 10% to 90%.

Table 2. Enhanced sludge wash performance.				
Species	Privatization Sludge Solids Removed by ESW (percent) <sup>a</sup>	Privatization Sludge Solids Removed by ESW+CrOx (percent) <sup>b</sup>	Phase I Sludge Solids Before ESW (MT) <sup>c</sup>	Phase II Sludge Solids After ESW (MT) <sup>d</sup>
Al <sup>3+</sup>	60	60	65	939
Cr <sup>3+</sup>	10	90	1.6	126
Na <sup>+</sup>	45	45	950	1640
PO <sub>4</sub> <sup>3-</sup>	70	70	8.0	145
<sup>a</sup> Table 14, Reference 10 <sup>b</sup> Page 112, Reference 10 <sup>c</sup> Stream #5 - Figure 14, Reference 10 <sup>d</sup> Stream #39, Figure 14, Reference 10				

As examples:

Phase I:

Aluminum in solids following ESW -

$$(1-60/100)(65 \text{ MT-Al}) = 26 \text{ MT-Al (see Table 2, column four)}$$

$$(102 \text{ kg-Al}_2\text{O}_3/54 \text{ kg-Al})(26 \text{ MT-Al}) = 49.1 \text{ MT-Al}_2\text{O}_3 \text{ (see column four, Table 5)}$$

Phase II:

Chromium in solids without ESW or chromium oxidation (the TWRS Privatization baseline is ESW only, without CrOx) -

$$(126 \text{ MT-Cr})/(1-10/100) = 140 \text{ MT-Cr (see Table 2, column five)}$$

$$(152 \text{ kg-Cr}_2\text{O}_3/104 \text{ kg-Cr})(140 \text{ MT-Cr}) = 208 \text{ MT-Cr}_2\text{O}_3 \text{ (see column three, Table 6)}$$

#### 4.4 HLW Glass

To determine how the amount of HLW glass is affected by the type of processing and amount of tank waste as defined by the Privatization phase, it is necessary to use the glass specifications modified for the Privatization effort, as listed in Table 17 of Reference 10. The maximum allowable HLW glass waste oxide loading for this study was selected as 45 wt% based on that used for the TWRS Flowsheet [4]. While this value (45 wt%) is considerably greater than that currently used at Savannah River, and has been somewhat of a moving target for the Privatization effort, it has been a technical goal at Hanford for some time. The glass waste oxide loading has been a highly controversial subject across the DOE complex, and it is unlikely any value chosen for this study will satisfy all. Table 3 displays the scenarios analyzed for this study based on potential processing combinations for solids-based and liquid-based waste. Included in Table 3 are the estimated amounts of HLW glass resulting from each of the relevant scenarios. The No-Waste column or row of Table 3 reflect the amount of HLW glass due to solids-based waste alone or liquid-based waste alone respectively. The Max column or row indicate the minimum amount of HLW glass possible, which is based upon maximum radionuclide loading in the glass limited by thermal considerations.

**Table 3. Processing scenarios and respective HLW glass amounts (MT).**

Solids-Based Waste	Privatization Phase	Liquid-Based					
		No Waste	No Treatment <sup>a</sup>	CS100 <sup>a</sup>	RF <sup>a</sup>	CST <sup>a</sup>	Max
No Waste	I		73809				111
	II		424344				366
No Treatment	I	1194	75003	1195	1195	1197	
	II	41013	465357	41612	41612	41612	
ESW	I			1044	988	988	
	II			37000 <sup>b</sup>	36664	36750	
ESW + CrOx	I			1041	988	988	
	II			23782	22769	22895	
Max	I	73					179
	II	425					791
<sup>a</sup> - estimated by blending solids-based and liquid-based waste							
<sup>b</sup> - directly from Stream #42 - Figure 14 of Reference 10							

Tables 4, 5 and 6 display the Phase I and Phase II waste composition and consequent HLW glass amount for the relevant scenarios defined in Table 3. The HLW glass amounts shown in Table 3 were determined as follows.

Case 1: Total tank waste with no processing (solids-based plus liquid-based):

Phase I - Blended waste defined by Stream #5 - Figure 14 of Reference 10; HLW glass composition is shown in column two of Table 5; the combined sodium and potassium oxide control the amount of HLW glass produced {75,003 MT}

Phase II - Blended waste defined by Stream #42 - Figure 14 of Reference 10 adjusted for (1) no ESW and for (2) aluminum, potassium, and sodium removed by IX (Stream #14); HLW glass composition is shown in column two of Table 6; the combined sodium and potassium oxide control the amount of HLW glass produced {465,357 MT}

Case 2: Total tank waste with no sludge processing, but CS100 IX processing of liquid-based waste (solids-based plus liquid-based):

Phase I - Blended waste defined by Stream #5 - Figure 14 of Reference 10 adjusted for CS100 sodium contribution determined in Section 4.2 of this report (72.6 MT-Na); HLW glass composition is shown in column four of Table 4; the combined  $\text{Al}_2\text{O}_3 + \text{ZrO}_2 + \text{Fe}_2\text{O}_3$  and the total waste oxide both control the amount of HLW glass produced {1195 MT}

Phase II - Blended waste defined by Stream #42 - Figure 14 of Reference 10 adjusted for no ESW determined in Section 4.3 of this report; HLW glass composition is shown in column three of Table 6; the chromium oxide controls the amount of HLW glass produced {41,612}

Case 3: Solids-based waste only with no processing:

Phase I - Blended waste defined by Stream #5 - Figure 14 of Reference 10 without soluble components; HLW glass composition is shown in column three of Table 4; the combined  $\text{Al}_2\text{O}_3 + \text{ZrO}_2 + \text{Fe}_2\text{O}_3$  controls the amount of HLW glass produced {1194 MT}

Phase II - The prior Case 2 adjusted for no sodium or potassium from liquid based waste; HLW glass composition is calculated from Case 2 for which the loading is chromium oxide controlled

$$(41,612 \text{ MT-HLW glass}) - (599 \text{ MT-Na/K}) = 41,013 \text{ MT-HLW glass}$$

Case 4: Liquid-based waste only with no processing:

Phase I - The prior Cases 1 and 3 as follows

$$\begin{aligned} &(\text{solids+liquid}) - (\text{liquid}) \\ &(75,003 \text{ MT-HLW glass}) - (1194 \text{ MT-HLW glass}) = \\ &73,809 \text{ MT-HLW glass} \end{aligned}$$

Phase II - The prior Cases 1 and 3 as follows

$$\begin{aligned} &(\text{solids+liquid}) - (\text{liquid}) \\ &(465,357 \text{ MT-HLW glass}) - (41,013 \text{ MT-HLW glass}) = \\ &424,344 \text{ MT-HLW glass} \end{aligned}$$

Case 5: Total tank waste with no sludge processing, but RF IX processing of liquid-based waste:

Phase I - blended waste defined by Stream #5 - Figure 14 of Reference 10 adjusted for RF sodium contribution determined in Section 4.2 of this report (17.9 MT-Na); HLW glass composition is shown in column five of Table 4; the combined  $\text{Al}_2\text{O}_3 + \text{ZrO}_2 + \text{Fe}_2\text{O}_3$  controls the amount of HLW glass produced {1195 MT}

Phase II - the HLW glass amount is not significantly different from CS100 resin due the high chromium content from the solids-based waste

Case 6: Total tank waste with no sludge processing, but CST IX processing of liquid-based waste:

Phase I - blended waste defined by Stream #5 - Figure 14 of Reference 10 adjusted for CST resin contribution determined in Section 4.2 of this report,

$$\begin{aligned} &[(1-0.175) \times 36.6 \text{ MT-Na}], \text{ where the CST resin is} \\ &\sim 17.5 \text{ wt\% SiO}_2 \text{ (Reference 11);} \end{aligned}$$

HLW glass composition is shown in column six of Table 4; the combined  $\text{Al}_2\text{O}_3 + \text{ZrO}_2 + \text{Fe}_2\text{O}_3$  controls the amount of HLW glass produced {1197 MT}

Phase II - the HLW glass amount is not significantly different from CS100 resin due the high chromium content from the solids-based waste

Case 7: Total tank waste with ESW of solids-based waste and CS100 IX processing of liquid-based waste:

Phase I - blended waste defined by Stream #5 - Figure 14 of Reference 10 adjusted for ESW (Section 4.3) and CS100 sodium contribution (Section 4.2); HLW glass composition is shown in column four of Table 5; the total waste oxide controls the amount of HLW glass produced {1044 MT}

Phase II - Privatization baseline; HLW glass composition is shown by Stream #42 - Figure 14 of Reference 10; the HLW glass amount is controlled by chromium oxide {37,000 MT}

Case 8: Total tank waste with ESW of solids-based waste and CST IX processing of liquid-based waste:

Phase I - blended waste defined by Stream #5 - Figure 14 of Reference 10 adjusted for ESW (Section 4.3) and CST resin contribution determined in Section 4.2 of this report,

$[(1-0.175) \times 36.6 \text{ MT-Na}]$ , where the CST resin is  
~17.5 wt% SiO<sub>2</sub> (Reference 11);

HLW glass composition is shown in column six of Table 5; the iron oxide controls the amount of HLW glass produced {988 MT}

Phase II - Privatization baseline Case 7, adjusted for CST resin rather than CS100 sodium contribution; since the HLW glass amount of Case 7 is controlled by chromium oxide,

$(37,000 \text{ MT-HLW glass}) - \{[445.9 \text{ CS100}] + [(1-0.175)238.2 \text{ CST}] \text{ MT-Na/K}\} = 36,750 \text{ MT-HLW glass}$   
where CST is 17.5 wt% SiO<sub>2</sub>

Case 9: Total tank waste with ESW of solids-based waste and RF IX processing of liquid-based waste:

Phase I - blended waste defined by Stream #5 - Figure 14 of Reference 10 adjusted for ESW (Section 4.3) and RF resin contribution (Section 4.2); HLW glass composition is shown in column three of Table 5; the iron oxide controls the amount of HLW glass produced {988 MT}

Phase II - Privatization baseline Case 7, adjusted for RF rather than CS100 sodium contribution; since the HLW glass amount of Case 7 is controlled by chromium oxide,

$(37,000 \text{ MT-HLW glass}) - [(445.9 \text{ CS100}) + (109.8 \text{ RF}) \text{ MT-Na/K}] =$   
36,664 MT-HLW glass

Case 10: Total tank waste with ESW plus chromium oxidation of solids-based waste, and CS100 IX processing of liquid-based waste:

Phase I - blended waste defined by Stream #5 - Figure 14 of Reference 10 adjusted for ESW (Section 4.3) with chromium oxidation (90 wt% rather than 10 wt% chromium removal from sludge) and CS100 sodium contribution; HLW glass composition is shown in column five of Table 5; the total waste oxide controls the amount of HLW glass produced {1041 MT}

Phase II - Privatization baseline Case 7, adjusted for 90 wt% chromium removal rather than 10 wt%; HLW glass composition is shown in column four of Table 6; the total waste oxide controls the amount of HLW glass produced {23,782 MT}

Case 11: Total tank waste with ESW plus chromium oxidation of solids-based waste, and RF IX processing of liquid-based waste:

Phase I - not significantly different from ESW without chromium oxidation, based on comparing the results of Case 7 and Case 10

Phase II - Privatization baseline Case 7, adjusted for 90 wt% chromium removal rather than 10 wt%, and the use of RF IX processing of liquid-based waste [Section 4.2]; HLW glass composition is shown in column five of Table 6; the total waste oxide controls the amount of HLW glass produced {22,769}

Case 12: Total tank waste with ESW plus chromium oxidation of solids-based waste, and CST IX processing of liquid-based waste:

Phase I - not significantly different from ESW without chromium oxidation, based on comparing the results of Case 7 and Case 10

Phase II - Privatization baseline Case 7, adjusted for 90 wt% chromium removal rather than 10 wt%, and the use of CST IX processing of liquid-based waste [Section 4.2]; HLW glass composition is shown in column six of Table 6; the total waste oxide controls the amount of HLW glass produced {22,895}

Case 13: Maximum radionuclide loading of HLW glass is based on thermal considerations. The "Clean Option" study discussed in Reference 3 estimates ~400 canisters of HLW glass due to <sup>137</sup>Cs and <sup>90</sup>Sr in the Hanford SST & DST waste. This is based on 1650 kg/canister. Since this will be a rough estimate, it will be assumed the inventory of the Clean Option study and that of the TWRS Flowsheet are similar.

$$400 \text{ canisters}(1650 \text{ kg/canister}) = 660,000 \text{ kg (660 MT-HLW glass)}$$

#### TWRS

$$(5.35 \times 10^7 \text{ Ci-Sr})(0.546 \text{ MeV/decay}) = 2.92 \times 10^7 \text{ heat equivalents (hq) from Sr}$$

$$(3.40 \times 10^7 \text{ Ci-Cs})(1.176 \text{ MeV/decay}) = 4.00 \times 10^7 \text{ hq-Cs}$$

$$(2.92 + 4.00) \times 10^6 = 6.92 \times 10^7 \text{ hq-TWRS}$$

#### Phase I

solids:

$$(1.23 \times 10^7 \text{ Ci-Sr})(0.546 \text{ MeV/decay}) = 6.72 \times 10^6 \text{ hq-Sr}$$

$$(8.35 \times 10^5 \text{ Ci-Cs})(1.176 \text{ MeV/decay}) = 9.82 \times 10^5 \text{ hq-Cs}$$

$$(6.72 + 0.98) \times 10^6 = 7.70 \times 10^6 \text{ hq-I/solids}$$

liquid:

$$(2.97 \times 10^5 \text{ Ci-Sr})(0.546 \text{ MeV/decay}) = 1.62 \times 10^5 \text{ hq-Sr}$$

$$(9.34 \times 10^6 \text{ Ci-Cs})(1.176 \text{ MeV/decay}) = 1.10 \times 10^7 \text{ hq-Cs}$$

$$(0.02 + 1.10) \times 10^6 = 1.12 \times 10^7 \text{ hq-I/liquid}$$

## Phase II

solids:

$$(5.18 \times 10^7 \text{ Ci-Sr})(0.546 \text{ MeV/decay}) = 2.83 \times 10^7 \text{ hq-Sr}$$

$$(1.39 \times 10^7 \text{ Ci-Cs})(1.176 \text{ MeV/decay}) = 1.63 \times 10^7 \text{ hq-Cs}$$

$$(2.83 + 1.63) \times 10^7 = 4.46 \times 10^7 \text{ hq-II/solids}$$

liquid:

$$(1.88 \times 10^6 \text{ Ci-Sr})(0.546 \text{ MeV/decay}) = 1.03 \times 10^6 \text{ hq-Sr}$$

$$(3.18 \times 10^7 \text{ Ci-Cs})(1.176 \text{ MeV/decay}) = 3.74 \times 10^7 \text{ hq-Cs}$$

$$(0.10 + 3.74) \times 10^7 = 3.84 \times 10^7 \text{ hq-II/liquid}$$

## Privatization (Phase I&II)

$$(0.77 + 1.12 + 4.46 + 3.84) \times 10^7 = 10.19 \times 10^7 \text{ hq}$$

## Privatization Inventory Correction

$$660 \text{ MT-HLW glass} (10.19 \times 10^7 \text{ hq-Private} / 6.92 \times 10^7 \text{ hq-TWRS}) = 970 \text{ MT-HLW glass}$$

Phase I:

$$(0.77 \times 10^7 \text{ hq-solids} / 10.19 \times 10^7 \text{ hq}) 970 \text{ MT} = 73 \text{ MT-HLW glass for solids-based waste}$$

$$(1.17 \times 10^7 \text{ hq-solids} / 10.19 \times 10^7 \text{ hq}) 970 \text{ MT} = 111 \text{ MT-HLW glass for liquid-based waste}$$

Phase II:

$$(4.46 \times 10^7 \text{ hq-solids} / 10.19 \times 10^7 \text{ hq}) 970 \text{ MT} = 425 \text{ MT-HLW glass for solids-based waste}$$

$$(3.84 \times 10^7 \text{ hq-solids} / 10.19 \times 10^7 \text{ hq}) 970 \text{ MT} = 366 \text{ MT-HLW glass for liquid-based waste}$$



**Table 4. Phase I HLW glass specifications and composition.**

	Specification Limit		Solids only without ESW or Cr-Ox		Solids & Liquid with CS100, w/o ESW or Cr-Ox		Solids & Liquid with RF, w/o ESW or Cr-Ox		Solids & Liquid with CST, w/o ESW or Cr-Ox	
	Upper wt%	Lower wt%	metric ton	wt%	metric ton	wt%	metric ton	wt%	metric ton	wt%
Al <sub>2</sub> O <sub>3</sub>	0	15.00	122.8	10.3	122.8	10.3	122.8	10.3	122.8	10.3
B <sub>2</sub> O <sub>3</sub>	5	20.00	95.0	8.0	60.0	5.0	60.0	5.0	60.0	5.0
CaO	0	10.00	20.0	1.7	20.0	1.7	20.0	1.7	20.0	1.7
Cr <sub>2</sub> O <sub>3</sub>	0	0.50	2.3	0.2	2.3	0.2	2.3	0.2	2.3	0.2
Fe <sub>2</sub> O <sub>3</sub>	2	15.00	148.6	12.4	148.6	12.4	148.6	12.4	148.6	12.4
Li <sub>2</sub> O	1	7.00	12.0	1.0	12.0	1.0	12.0	1.0	12.0	1.0
MgO	0	8.00	12.3	1.0	12.0	1.0	12.0	1.0	12.0	1.0
Na <sub>2</sub> O & K <sub>2</sub> O	5	20.00	131.9	11.1	229.7	19.2	156.0	13.1	139.3	11.6
P <sub>2</sub> O <sub>5</sub>	0	3.00	12.0	1.0	12.0	1.0	12.0	1.0	12.0	1.0
SiO <sub>2</sub>	42	57.00	680.0	57.0	585	49.0	640	53.6	630	52.6
SO <sub>3</sub>	0	0.50	0.1	0.0	0.1	0.0	0.1	0.0	0.1	0.0
ZrO <sub>2</sub>	0	13.00	14.5	1.2	14.5	1.2	14.5	1.2	14.5	1.2
Al <sub>2</sub> O <sub>3</sub> +ZrO <sub>2</sub>	0	16.00	137.3	11.5	137.3	11.5	137.3	11.5	137.3	11.5
MgO+CaO	0	10.00	32.0	2.7	32.0	2.7	32.0	2.7	32.0	2.7
Rh <sub>2</sub> O <sub>3</sub> +Ru <sub>2</sub> O <sub>3</sub>	0	0.25	0	0	0	0	0	0	0	0
Al <sub>2</sub> O <sub>3</sub> +ZrO <sub>2</sub> +Fe <sub>2</sub> O <sub>3</sub>	0	24.00	285.9	24.0	285.9	23.9	285.9	23.9	285.9	23.9
Added waste oxide			0		0		0		24.7	
Total waste oxide			406.5	34.1	537.6	45.0	482.9	40.4	495.2	41.4
Total glass			1193.5		1194.6		1194.6		1197.2	
The highlighted value represents the controlling parameter										

**Table 5. Phase I HLW glass specifications and composition (continued).**

	Solids & Liquid without any treatment		Solids & Liquid with RF & ESW, w/o Cr-Ox**		Solids & Liquid with CS100 & ESW, w/o Cr-Ox**		Solids & Liquid with CS100 & ESW+Cr-Ox		Solids & Liquid with CST, ESW & w/o Cr-Ox	
	metric ton	wt%	metric ton	wt%	metric ton	wt%	metric ton	wt%	metric ton	wt%
Al <sub>2</sub> O <sub>3</sub>	2119.8	2.8	49.1	5.0	49.1	4.7	49.1	4.7	49.1	5.0
B <sub>2</sub> O <sub>3</sub>	13600	18.1	55.0	5.6	52.0	5.0	52.0	5.0	55.0	5.6
CaO	26.0	0.0	20.0	2.0	20.0	1.9	20.0	1.9	20.0	2.0
Cr <sub>2</sub> O <sub>3</sub>	20.3	0.0	2.1	0.2	2.1	0.2	0.2	0.0	2.1	0.2
Fe <sub>2</sub> O <sub>3</sub>	156.4	0.2	148.6	15.0	148.6	14.2	148.6	14.3	148.6	15.0
Li <sub>2</sub> O	750	1.0	10.0	1.0	10.0	1.0	10.0	1.0	10.0	1.0
MgO	12.0	0.0	12.0	1.2	12.0	1.2	12.0	1.2	12.0	1.2
Na <sub>2</sub> O & K <sub>2</sub> O	14939	19.9	98.4	10.0	168.3	16.5	168.3	16.5	81.7	8.7
P <sub>2</sub> O <sub>5</sub>	209.3	0.3	3.6	0.4	3.6	0.3	3.6	0.3	3.6	0.4
SiO <sub>2</sub>	42700	56.9	562.0	56.9	512.0	49.0	511.0	49.1	562.0	46.9
SO <sub>3</sub>	350.1	0.5	0.1	0.0	0.1	0.0	0.1	0.0	0.1	0.0
ZrO <sub>2</sub>	14.5	0.0	14.5	1.5	14.5	1.4	14.5	1.4	14.5	1.5
Al <sub>2</sub> O <sub>3</sub> +ZrO <sub>2</sub>	2134.4	2.8	63.7	6.4	63.7	6.1	63.7	6.1	63.7	6.4
MgO+CaO	38.1	0.1	32.0	3.2	32.0	3.1	32.0	3.1	32.0	3.2
Rh <sub>2</sub> O <sub>3</sub> +Ru <sub>2</sub> O <sub>3</sub>	0	0	0	0	0	0	0	0	0	0
Al <sub>2</sub> O <sub>3</sub> +ZrO <sub>2</sub> +Fe <sub>2</sub> O <sub>3</sub>	2290.8	3.1	212.2	21.5	212.2	20.3	212.2	20.4	212.2	21.5
Added waste oxide	0		0		0		0		24.7	
Total waste oxide	17953	23.9	360.9	36.5	470.3	45.0	468.4	45.0	360.8	36.5
Total glass	75003		987.9		1044.3		1041.4		987.8	

The highlighted value represents the controlling parameter

**Table 6. Phase II HLW glass specifications and composition.**

	Solids & Liquid without any treatment		Solids & Liquid with CS100, w/o ESW or Cr-Ox		Solids & Liquid with CS100 & ESW + Cr-Ox		Solids & Liquid with RF & ESW+Cr-Ox		Solids & Liquid with CST & ESW + Cr-Ox	
	metric ton	wt%	metric ton	wt%	metric ton	wt%	metric ton	wt%	metric ton	wt%
Al <sub>2</sub> O <sub>3</sub>	3425	0.7	3161	7.6	1730	7.3	1730	7.6	1730	7.6
B <sub>2</sub> O <sub>3</sub>	93000	20.0	3000	7.2	1190	5.0	1140	5.0	1145	5.0
CaO	179	0.0	179	0.4	179	0.8	179	0.8	179	0.8
Cr <sub>2</sub> O <sub>3</sub>	208	0.0	208	0.5	20.8	0.1	20.8	0.1	20.8	0.1
Fe <sub>2</sub> O <sub>3</sub>	959	0.2	959	2.3	959	4.0	959	4.0	959	4.2
Li <sub>2</sub> O	4800	1.0	430	1.0	240	1.0	230	1.0	230	1.0
MgO	2	0.0	2	0.0	2	0.0	2	0.0	2	0.0
Na <sub>2</sub> O & K <sub>2</sub> O	93193	20.0	5582	13.4	3735	15.7	3282	14.4	3182	13.9
P <sub>2</sub> O <sub>5</sub>	728	0.2	728	1.8	216.7	0.9	216.7	1.0	216.7	1.0
SiO <sub>2</sub>	265218	57.0	23718	57.0	12586	52.9	12086	53.1	12188	53.2
SO <sub>3</sub>	21	0.0	21	0.1	21	0.1	21	0.1	21	0.1
ZrO <sub>2</sub>	904	0.2	904	2.1	904	3.8	904	4.0	904	4.0
Al <sub>2</sub> O <sub>3</sub> +ZrO <sub>2</sub>	4329	0.9	4065	9.8	2634	11.1	2634	11.6	2634	11.5
MgO+CaO	181	0.0	181	0.4	181	0.8	181	0.8	181	0.8
Rh <sub>2</sub> O <sub>3</sub> +Ru <sub>2</sub> O <sub>3</sub>	0	0	0	0	0	0	0	0	0	0
Al <sub>2</sub> O <sub>3</sub> +ZrO <sub>2</sub> +Fe <sub>2</sub> O <sub>3</sub>	5288	1.1	5024	12.1	3593	15.1	3593	15.8	3593	15.7
Added waste oxide	0		0		0		0		160	
Total waste oxide	102557	22.0	14682	35.2	10701	45.0	10249	45.0	10309	45.0
Total glass	465357		41612		23782		22769		22895	

The highlighted value represents the controlling parameter

It was decided to use the TWRS Flowsheet maximum waste oxide loading limit (45 wt%) for the HLW glass, because the Privatization Flowsheet did not require a similar limit due to chromium controlling the glass amount.

#### 4.5 Costs

The significant cost drivers were determined in previous cost studies (Reference 5, 6 & 7), and area listed in the following.

Significant costs (Figure 6 of Reference 12)

• HLW glass amount:

$$\text{- combined immobilization and disposal @ } [\$ (3130+5880) \times 10^6] / [24.1 \times 10^6 \text{ kg-HLW glass}] =$$

$$\$374/\text{kg-HLW glass}$$

- Processing:
  - ESW @ \$27.6/kg-sludge-waste-oxide processed
  - organic IX @ \$16.0/kg-liquid-waste-oxide processed;
    - . included is regeneration @ \$530M/79.2x10<sup>6</sup> kg-liquid processed (\$6.7/kg)
      - where \$530M is based upon page 12 of Reference 5
    - . not included is resin
      - CS100 @ \$28/Kg [5]
      - RF @ \$39/Kg [6]
      - CST @ \$220/Kg [5]

#### Insignificant costs (Figure 6 of Reference 12)

- LLW amount:
  - immobilization @ \$43.5/kg-LLW
  - disposal @ \$4.1/kg-LLW
  - combined immobilization and disposal @ \$47.6/kg-LLW (~2 % of HLW glass cost)
- Off gas:
  - that generated from IX resin disposal is ~1 wt% total system off gas
    - (see page 16 of Reference 5)

#### Cost Difference Determination

Case 1: Total tank waste with no processing (solids-based plus liquid-based):

The cost difference was not determined for this scenario.

Case 2: Total tank waste with no sludge processing, but CS100 IX processing of liquid-based waste (solids-based plus liquid-based):

The cost difference was assumed to be zero for this scenario. This scenario was used as the basis of comparison for all other scenarios considered, i.e. the baseline.

Case 3: Solids-based waste only with no processing:

The cost difference was not determined for this scenario.

Case 4: Liquid-based waste only with no processing:

The cost difference was not determined for this scenario.

Case 5: Total tank waste with no sludge processing, but RF IX processing of liquid-based waste:

Phase I - HLW glass difference is essentially zero (see Table 3)

RF resin per TWRS Flowsheet = 58,100 Kg [6] for ten regenerations

correcting for four regenerations (see Section 3.0)

$$(10/4)(58,100 \text{ Kg}) = 145,250 \text{ Kg}$$

correcting for the Phase I waste fraction

$$(\$37/\text{Kg})[0.166(145,250 \text{ Kg})] = \$0.9 \text{ M}$$

Resin cost difference (see Phase I, Case 6 for CS100 resin cost)

$$\$ (3.5-0.9) \text{ M} \sim \$3 \text{ M-LTB}$$

Total cost difference

$$\$3 \text{ M-LTB}$$

Phase II - HLW glass difference is essentially zero (see Table 3)

See Phase I, Case 5

Correcting for the Phase II waste fraction

$$(\$37/\text{Kg})[0.834(145,250 \text{ Kg})] = \$4.5 \text{ M}$$

Resin cost difference (see Phase II, Case 6 for CS100 resin cost)

$$\$ (17.4-4.5) \text{ M} \sim \$13 \text{ M-LTB}$$

Total cost difference

$$\$13 \text{ M-LTB}$$

Case 6: Total tank waste with no sludge processing, but CST IX processing of liquid-based waste:

HLW glass difference is essentially zero for both Phase I and II (see Table 3)

Phase I - CS100 resin per TWRS Flowsheet [4] = 744,000 Kg for all Hanford waste

Phase I liquid-based waste oxide

$$(17,953-406) \text{ MT} = 17,547 \text{ MT}$$

where

17,953 MT is solids- and liquid-based waste-oxide as shown in column two of Table 5

406 MT is solids-based waste as shown in column three of Table 4

Phase I waste fraction (see Phase II for Case 6)

$$[17,547 / (17,547 + 87,869)] = 0.166$$

CS100 resin for Phase I

$$0.166(744,000 \text{ Kg}) = 123,504 \text{ Kg}$$

$$(\$28/\text{Kg})(123,504 \text{ Kg}) = \$3.5 \text{ M}$$

CST resin use is 36,000 Kg per Section 4.2

$$(\$220/\text{Kg})(36,000 \text{ Kg}) = \$7.9 \text{ M}$$

Resin cost difference

$$\$ (7.9-3.5) \text{ M} \sim \$4.4 \text{ M-LTB}$$

Regeneration

$$[(17,953-406) \times 10^3 \text{ kg-liquid}] (\$6.7/\text{kg-liquid}) = \$118 \text{ M-LTB}$$

Total cost difference

$$\$ (118-5) \text{M} = \$113 \text{ M -LTB}$$

Phase II - CS100 resin per TWRS Flowsheet [4] = 744,000 Kg for all Hanford waste

Phase II liquid-based waste oxide

$$(102,551-14,682) \text{ MT} = 87,869 \text{ MT}$$

where

102,551 MT is total solids- and liquid-based waste as shown in column two of Table 6 14,682 MT is solids- and liquid-based waste following CS100 IX, which is ~95 wt% due to solids, as shown in column three of Table 6

CS100 resin for Phase II

$$(1-0.166)(744,000 \text{ Kg}) = 620,496 \text{ Kg}$$

$$(\$28/\text{Kg})(620,496 \text{ Kg}) = \$17.4 \text{ M}$$

CST resin use is 238,000 Kg per Section 4.2

$$(\$220/\text{Kg})(238,000 \text{ Kg}) = \$52.4 \text{ M}$$

Resin cost difference

$$\$ (52.4-17.4) \text{M} \sim \$35.0 \text{ M-GTB}$$

Regeneration

$$(87,869 \times 10^3 \text{ kg-liquid})(\$6.7/\text{kg-liquid}) = \$589\text{-LTB}$$

Total cost difference

$$\$ (589-35) \text{M} = \$554 \text{ M -LTB}$$

Case 7: Total tank waste with ESW of solids-based waste and CS100 IX processing of liquid-based waste:

Phase I - HLW glass difference (see Table 3)

$$(\$374/\text{kg-HLW glass})(1195-1044) \times 10^3 \text{ kg-HLW glass} = \$56 \text{ M -LTB}$$

Sludge processing

$$(406 \times 10^3 \text{ kg-sludge})(\$27.6/\text{kg-sludge}) = \$11 \text{ M -GTB}$$

where

406 MT is the solids-based waste as shown in column three of Table 4

Total cost difference

$$(56-11) = \$45 \text{ M-LTB}$$

Phase II - HLW glass difference (see Table 3)

$$(\$374/\text{kg-HLW glass})(41,612-37,000) \times 10^3 \text{ kg-HLW glass} = \$1725 \text{ M-GTB}$$

where

37,000 MT HLW glass is the Privatization baseline (Stream #42 - Figure 14 of Reference 10)

Sludge processing

$$(14682-446(62/46)] \times 10^3 \text{ kg-sludge})(\$27.6/\text{kg-sludge}) = \$389 \text{ M-LTB}$$

where

14682 MT sludge-waste-oxide is shown in column three of Table 6 for solids and liquid

466 MT sodium is shown in Section 4.2 with (62/46) as the oxide adjustment

Total cost difference

$$(1725-389) = \$1,336 \text{ M-LTB}$$

Case 8: Total tank waste with ESW of solids-based waste and CST IX processing of liquid-based waste:

Phase I - HLW glass difference (see Table 3)

$$(\$374/\text{kg-HLW glass})(1195-988) \times 10^3 \text{ kg-HLW glass} = \$77 \text{ M less}$$

Regeneration

$$[(17,953-406) \times 10^3 \text{ kg-liquid}](\$6.7/\text{kg-liquid}) = \$118 \text{ M less}$$

Resin cost difference

\$5 M greater (see I.1)

Total cost difference

$$(\$77+118-5) = \$190 \text{ M less than ESW with CS100}$$

$$(\$190+45) = \$235 \text{ M-LTB}$$

Phase II - HLW glass amount (see Table 3)

$$(\$374/\text{kg-HLW glass})(37,000-36,750) \times 10^3 \text{ kg-HLW glass} = \$94 \text{ M less}$$

Resin cost difference

\$35 M greater for (see II.1)

Regeneration

\$589 M less (see II.0.1)

Total cost difference

$$(\$94+589-35)\text{M} = \$648 \text{ M less than ESW with CS100}$$

$$(\$648+1,336) = \$1,984 \text{ M-LTB}$$

Case 9: Total tank waste with ESW of solids-based waste and RF IX processing of liquid-based waste:

Phase I - HLW glass amount (see Table 3)

$$(\$374/\text{kg-HLW glass})(1195-988) \times 10^3 \text{ kg-HLW glass} = \$77 \text{ M less}$$

Resin cost difference

\$3 M less ( see I.1)

Total cost difference

$$(\$77+3) = \$80 \text{ M less than ESW with CS100}$$

$$\$ (80+45) = \$125 \text{ M-LTB}$$

Phase II - HLW glass amount (see Table 3)

$$(\$374/\text{kg-HLW glass})(37,000-36,664) \times 10^3 \text{ kg-HLW glass} = \$126 \text{ M less}$$

Resin cost difference

$$\$13 \text{ M less (see II.2)}$$

Total cost difference

$$\$ (126+13) \text{ M} = \$139 \text{ M less than ESW with CS100}$$

$$\$ (139+1,336) = \$1,475 \text{ M-LTB}$$

Case 10: Total tank waste with ESW plus chromium oxidation of solids-based waste, and CS100 IX processing of liquid-based waste:

Phase I - No significant cost difference than processing w/o CrOx due to limitations imposed by the total waste oxide concentration (see Cases 10,11 &12).

Phase II - HLW amount (see Table 3)

$$(\$374/\text{kg-HLW glass})(37,000-23,782) \times 10^3 \text{ kg-HLW glass} = \$4,944 \text{ M less}$$

Total cost difference

$$\$4,944 \text{ M less than ESW with CS100}$$

$$\$ (4,944+1,336) = \$6,280 \text{ M-LTB}$$

Case 11: Total tank waste with ESW plus chromium oxidation of solids-based waste, and RF IX processing of liquid-based waste:

Phase I - No significant cost difference than processing w/o CrOx due to limitations imposed by the total waste oxide concentration (see Cases 10,11 &12).

Phase II - HLW amount (see Table 3)

$$(\$374/\text{kg-HLW glass})(23,782-22,895) \times 10^3 \text{ kg-HLW glass} = \$332 \text{ M less}$$

Regeneration

$$\$589 \text{ M less (see II.1)}$$

Resin cost difference

$$\$35 \text{ M greater (see II.1)}$$

Total cost difference

$$\$ (332+589-35) \text{ M} = \$886 \text{ M less than ESW plus chromium oxidation with CS100}$$

$$\$ (886+6,280) = \$7,166 \text{ M-LTB}$$



Case 12: Total tank waste with ESW plus chromium oxidation of solids-based waste, and CST IX processing of liquid-based waste:

Phase I - No significant cost difference than processing w/o CrOx due to limitations imposed by the total waste oxide concentration (see Cases 10,11 &12).

Phase II - HLW amount (see table 3)

$$(\$374/\text{kg-HLW glass})(23,782-22,769)\times 10^3 \text{ kg-HLW glass} = \$379 \text{ M less}$$

Resin cost difference

$$\$13 \text{ M-LTB (see II.2)}$$

Total cost difference

$$\$ (379+13) \text{ M} = \$392 \text{ M less than ESW plus chromium oxidation with CS100}$$

$$\$ (392+6,280) = \$6,672 \text{ M-LTB}$$

Case 13: Maximum radionuclide loading of HLW glass is based on thermal considerations. See Section 4.4:

The cost difference was not determined for this scenario.

## 5. Summary

Tables 7 summarizes the cost savings for each significant combination of solids-based and liquid-based processing combination, in terms of the previously defined Items. Table 8 repeats Table 7 in terms of dollars.

**Table 7. Costs defined by items.**

Solids-Based Waste	Privatization Phase	Liquid-Based					
		No Waste	No Treatment <sup>a</sup>	CS100 <sup>a</sup>	RF <sup>a</sup>	CST <sup>a</sup>	Max
No Waste	I II						
No Treatment	I II			0 0	I.2 II.2	I.1 II.1	
ESW	I II			I.3 II.3	I.3+I.5 II.3+II.5	I.3+I.4 II.3+II.4	
ESW + Cr	I II			I.3+I.6 II.3+II.6	I.3+I.5+I.6 II.3+II.5+II.8	I.3+I.4+I.6 II.3+II.4+II.7	
Max	I II						

**Table 8. Cost savings by amount (\$ millions).**

Solids-Based Waste	Privatization Phase	Liquid-Based					
		No Waste	No Treatment <sup>a</sup>	CS100 <sup>a</sup>	RF <sup>a</sup>	CST <sup>a</sup>	Max
No Waste	I II						
No Treatment	I II			0 0	3 13	113 554	
ESW	I II			45 1,336	125 1,475	235 1984	
ESW + Cr	I II			45 6,280	125 6,672	235 7,166	
Max	I II						

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